Influence of Velocity and Surface Temperature of Alumina Particles on the Properties of Plasma Sprayed Coatings

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In this paper are described the main characteristics of the plasma spraying process of alumina deposits, i.e., the temperature and flow field of the plasma jets obtained with the classical spraying torches, the injection of the particles into the plasma jet, the particle surface temperature and velocities in the plasma (measured for calibrated alumina particles), and the coating generation. The measurements on the alumina particles are compared with the predictions of a mathematical model. The experimental and computed particle velocities are in rather good agreement. However, this is not the case for the particle surface temperature. Possible reasons for the discrepancy are proposed (influence of the carrier gas, thermophoretic forces, and poor penetration of the particles into the plasma core even for an injection velocity twice that of the optimal calculated one, as shown by recent measurements). Finally the correlations between the particle velocities and surface temperature, and the properties of the alumina coating (porosity, crystal structure, mechanical properties) are studied.

1. INTRODUCTION

The formation of protective coatings from a stream of molten metal or ceramic particles was first developed using combustion flames into which the spray material was fed as powder, wire, or rod. In the 1960's commercial plasma spraying equipment became available in which a D.C. plasma jet was used to melt a powder feed and project the droplets at high velocity against the material to be coated. The major advantage over the flame spraying process is the higher particle velocity obtainable (up to 500 m/s), and the high temperatures achieved in the plasma jet (up to 15,000 K) also make it possible to melt even the most refractory materials to produce

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high-quality coatings. Plasma spraying is therefore particularly suitable for the formation of ceramic coatings for wear, thermal, and corrosion protection.

Plasma spraying[1] differs considerably from other surface treatments by its specific characteristics, viz.:

> The energy source is separated from the substrate: for this reason plasma spraying may be a cold substrate process.
> The particles interact in some way chemically and physically with the environment during the flight.
> The sprayed layer is built up particle by particle.
> The particles are cooled very fast after arriving at the substrate (splat cooling).
> The sprayed layer shows a structure of lamellae.
> Thermal spraying makes it possible to produce coatings of essentially different materials.

As usual, the scientific research lags behind the technical application, and plasma spraying has developed, to a large extent, by empirical means with relatively little scientific understanding of the mechanisms involved in coating formation and of the factors controlling the structure and properties of the coating. This is because the range of temperatures and the time scale of the various events are generally outside the usual experimental conditions encountered in materials processing and sophisticated techniques must be used to make significant progress. However, a better understanding of plasma spraying is now emerging, as shown by recent reviews.[1-4]

To achieve the best spraying conditions of plasma-sprayed deposits with the required macroscopic properties, one has to solve many problems. First, one has to search after the physics governing the processes; second, one has to formulate the requirements for a reliable and predictable production; and third, one has to determine the limits of the field of application. But this is easier to say than to do with more than 35 main macroscopic parameters (see Table I).

Since 1975, with the development of new measuring techniques such as laser doppler anemometry or in-flight pyrometry (see the Appendix) and with the automation of the spectroscopic measurements, it is, however, possible to follow statistically what happens to the particles in flight into the plasma jet and especially to attempt to correlate the physical properties of the plasma-sprayed deposits with the surface temperature and velocity of the particles upon impact.

That is why, starting from alumina for which the physical and chemical properties as functions of the temperature are well known, we will describe:

Table I. Main Parameters of Plasma Spraying Process

Power and energy	Spraying material	Substrate	Powder feeder	Spraying conditions
Voltage	Size of the powder particles	Physical and chemical properties of the substrate (thermal linear expansion coefficient, etc.)	Nature and mass flow rate of the carrier gas of the particles	Distance between the nozzle exit and the substrate
Current intensity	Particle shape	Surface roughness, oxidation and cleanliness of the substrate	Powder mass flow rate	Relative movement between the substrate and the torch
Nature of the plasma gas	Particle diameter	Substrate temperature during spraying process	Location and inclination of the powder injector	Ambient atmosphere or controlled atmosphere
Flow rate of the gas	Particle size distribution		Number of powder injectors	Method cooling of the substrate
Nature and design of the electrodes of the plasma torch	Physical and chemical properties of the powder (melting point, thermal conductivity, etc.)		Powder injection velocity	

the main characteristics of the plasma jets obtained with the classical spraying torches (Section 2.2),
the difficulties in injecting the particles into the plasma jet (Section 2.3),
the temperatures and velocities of the particles in flight into the plasma (Section 2.3),
the coating generation (Section 3:1),
the correlations existing between the particle velocities and surface temperatures and the properties of the sprayed deposit: porosity, crystal structure, and mechanical properties (Section 3.2).

2. SPRAYING DEVICE CHARACTERISTICS

2.1. Plasma Torches

The plasma torches used in spraying at atmospheric pressure have usually a maximum power of 90 kW and are based on a concept first given by Gage.[5] A direct current (D.C.) arc is struck between a cathode rod (usually made of thoriated tungsten) and a copper nozzle used as anode (the cathode rod is along the axis of the nozzle.[6,7] Stabilization of the arc is of cold wall type, and the gas injection is either tangential or longitudinal, forcing the arc to strike into the nozzle which is intensively water cooled. For this study we have used a 30-kW D.C. plasma generator made in our laboratory,[8] but numerous torches of this type are commercially available, for example, in the United States from Plasmadyne, Metco, and Avco, in Belgium from Arcos, in France from Air Liquide, in Poland from the Institute of Swierk, and in Switzerland from Plasmatechnic.

2.2. Characteristics of the Corresponding Plasma Jets

The characteristics (temperature and velocity distributions) of the plasmas jets are functions of the pressure, of the gases used (nature, flow rates, injection mode), of the dimensions and the shape of the electrodes, of the electrical power, of the current intensity, etc.
To determine the characteristics of such plasma jets we use the following techniques[9] (see Appendix).

a. To measure the temperature of the plasma jet we use, for $T > 6000$ K, spectroscopic methods (absolute line intensity of N I or Ar I) automated with a data acquisition system controlled by a computer performing the Abel's inversion,[10] and for $T < 4000$ K we use thermocouples or the melting points of different materials (correcting, of course, the measurements for the radiative and conductive losses). Such methods make it

possible to determine the temperature (under local thermal equilibrium, L.T.E.) either in the hot zone of the jet or in the plume.

b. To measure the velocity of the plasma jet we use laser anemometry (two-point method) with small alumina particles (less than 3 μm diameter) injected directly with the plasma gas into the arc chamber. However, due to the high luminosity of the plasma just after the nozzle exit, the measurements could be performed only 2 cm downstream from the nozzle exit. One has to emphasize that such methods are local methods involving small volumes: $10 \times 100 \times 100$ μm for the plasma velocity.

The plasma gases used in spraying are either argon or nitrogen, in both cases with hydrogen added in order to improve the heat transfer.[11] This is due to the fact that, as soon as the plasma temperature is greater than 4500 K (i.e., the dissociation temperature of H_2), the mean integrated thermal conductivity is about 5 W/m/K for H_2 compared to 0.1 for N_2 and 0.04 for Ar. That is why we have used mixtures of Ar–H_2 or N_2–H_2 for our experiments.

First we have tried to determine for these three gases the variations of the temperatures and velocities with the nature of the gas and the flow rate and with the diameter and length of the nozzle. Of course, due to the high radial gradients (up to 4000 K/mm and 200 m/s/mm), the comparisons we are going to summarize are relative to the temperatures and velocities on the plasma jet axis just at the nozzle exit.

2.2.1. Plasma Velocity

Due to the viscosities of the gases (Ar, N_2, H_2) at high temperature, one gets, for the same pressure, the same shape and dimensions of the electrodes, the same current intensity (meaning a very different power; for example, with 200 A and a 5-mm-diameter nozzle, the voltage is 20 V with argon, 60 V with nitrogen, and 120 V with hydrogen at atmospheric pressure) the highest velocity, 1200 m/s, with pure hydrogen, and then successively 800 m/s with nitrogen and 400 m/s with argon.

2.2.2. Plasma Temperature

Under the same conditions (200 A, 5-mm-nozzle diameter) the measured temperatures of the plasma jet, within 1000 K, are equivalent for argon, nitrogen, and hydrogen (about the same ionization potential).

2.2.3. Influence of Nozzle Dimensions

Under the same conditions of current intensity and nature and mass flow rate of the gas, an increase of the nozzle diameter usually lowers the